New physics searches

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Flavor Physics Lectures
VIII / XII

Karlsruhe Institute of Technology

Winter Semester 2022/2023
3. February, 2023

Reading material and references

Lecture material based on several textbooks and online lectures/notes. Credits for material and figures include:

Literature

Perkins, Donald H. (2000), *Introduction to High Energy Physics*.

Griffiths, David J. (2nd edition), *Introduction to Elementary Particles*.

Stone, Sheldon (2nd edition), *B decays*.

Online Resources

Belle/BaBar Collaborations, *The Phyiscs of the B-Factories*.
http://arxiv.org/abs/1406.6311

Bona, Marcella (University of London), *CP Violation Lecture Notes*,
http://pprc.qmul.ac.uk/ bona/ulpg/cpv/

Richman, Jeremy D. (UCSB), *Heavy Quark Phyiscs and CP Violation*.
http://physics.ucsd.edu/students/courses/winter2010/physics222/references/driver_houches12.pdf

Thomson, Mark (Cambridge University), *Particle Physics Lecture Handouts*,
http://www.hep.phy.cam.ac.uk/ thomson/partIIIparticles/welcome.html

Grossman, Yuval (Cornell University), *Just a Taste. Lectures on Flavor Physics*,
http://www.lepp.cornell.edu/ pt267/files/notes/FlavorNotes.pdf

Kooijman, P. & Tuning, N., *CP Violation*,
https://www.nikhef.nl/ h71/Lectures/2015/ppII-cpviolation-29012015.pdf

Recap & outline

So far, we:

Covered a wide range of material including: the CKM matrix; Kaon and B-meson mixing; 3 types of CP violation; how to measure the 3 angles of the unitarity triangle; and quarkonium studies.

We've focused heavily on experimental challenges and techniques, including: tracking; Dalitz; decays with undetectable particles (neutrinos); multi-dimensional fits; background-subtracted fits; and more.

Today, we'll:

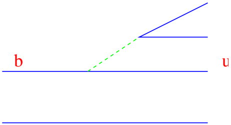
Focus on rare decays and new physics searches at B meson factories. We'll see how these are complementary to searches at the LHC.

Time permitting, we'll close with a general review of mixing, where we'll briefly discuss the B_s and D meson systems. We'll also look into the D decays where mixing was first discovered.

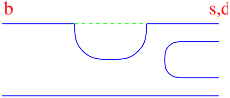
What are rare B decays?

Loose definition:

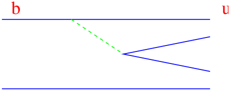
Every B decay that doesn't proceed by the dominant $b \to c$ transition.



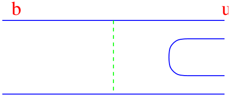
External spectator $b \to u$



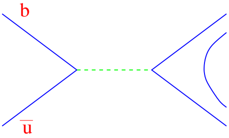
Penguin $b \to s(d)$



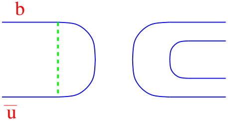
Internal spectator $b \to u$



W exchange $b \to u$



W annihilation



Hairpin diagram

Why rare decays?

Lessons from history:

Experimental observations:

$\hookrightarrow$ observed $K^+ \to \mu^+ \nu_\mu$ but not $K^0 \to \mu^+ \mu^-$

GIM (Glashow, Iliopoulos, Maiani) mechanism (1970)

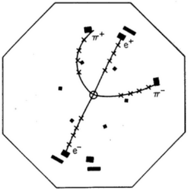
$\hookrightarrow$ no tree level Flavor Changing Neutral Currents

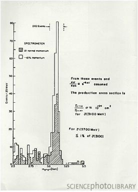
$\hookrightarrow$ suppession of FCNC via loops

$\hookrightarrow$Requires that quarks come in pairs (doublets)

$\hookrightarrow$**Predicts existence of charm quark**

Discovery of $J/\psi(c\bar{c})$ state (1974)





Quest for New Physics

Energy frontier

$\hookrightarrow$ Direct observation of particles and processes using highest achievable energies

Intensity frontier

$\hookrightarrow$ Indirect observation of NP effects on (rare) known processes

Energy frontier vs. Intensity frontier

Complementarity

Illustrative reach of NP searches with $\mathcal{O}(10^2)$ higher luminosity

BelleII TDR [arXiv:1011.0352]

High energy frontier (LHC) – direct searches of NP up to $\mathcal{O}(1\ \text{TeV})$

Intensity frontier (SuperKEKB)

$\Rightarrow$ Up to $\mathcal{O}(1\ \text{TeV})$ if Minimal Flavor Violation assumed.

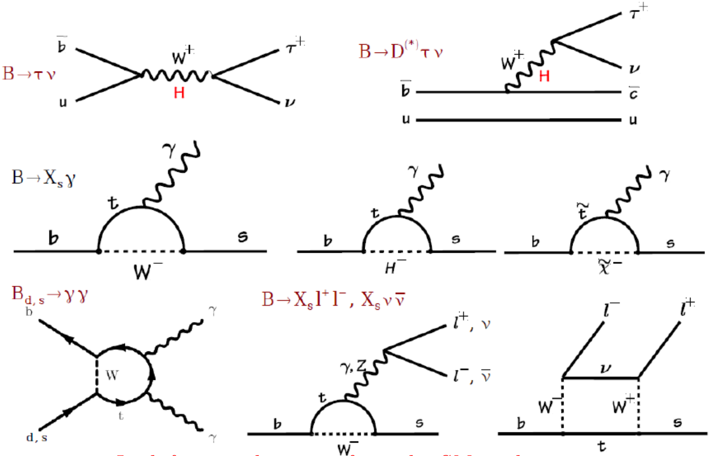
$\Rightarrow$ Up to $\mathcal{O}(100\ \text{TeV})$ if Flavor Violation coupling enhanced.

New physics searches in rare B decays

Search for effect of unknown particles on processes very rare within the SM

- We covered $\tau\nu$ and $D^*\tau\nu$ in our lecture on *decays with neutrinos in the final state.*

- Today we'll look at additional channels (including some radiative [γ] decays) for NP effects.



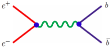
Look for any deviation from the SM predictions...

New Physics signatures?

Possible observables:

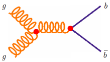
- Decay rates
- Direct CP violation
- Time-dependent CP violation
- Asymmetries in angular distributions
- ...

Belle II



- Clean experimental environment.
- Holistic interpretation of events with missing energy (ν).
- Decays with multiple photons.
- Inclusive decays ($B \to X_{s,d}\gamma$).
- Long-lived particles (K_S and K_L).

LHCb



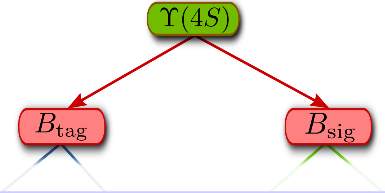
- Large cross section.
- Decays to all charged particle final states.
- Fast mixing.

Belle II Physics Book

Observables	Expected th. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	Belle II/LHCb
$S(B_s \to J/\psi\phi)$	***	0.01	LHCb
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\beta_s^{\rm eff}(B_s \to \phi\phi)$ [rad]	**	0.1	LHCb
$\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$ [rad]	**	0.1	LHCb
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	***	0.05	LHCb
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$q_0^2 A_{\rm FB}(B \to K^*\mu\mu)$	**	0.05	LHCb/Belle II
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	***	< 2	Belle II
$\mathcal{B}(B_s \to \mu\mu)$	***	10%	LHCb/Belle II
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	**	0.1	LHCb
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle Ii
$\phi(D^0 \to K_S^0\pi^+\pi^-)$ [°]	***	4	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-9}]$	***	< 5	Belle II
$\tau \to e\gamma$ $[10^{-9}]$	***	< 10	Belle II
$\tau \to \mu\mu\mu$ $[10^{-9}]$	***	< 0.3	Belle II/LHCb

Tensions with the SM in semileptonic B decays

Recall the different tag-side reconstructions



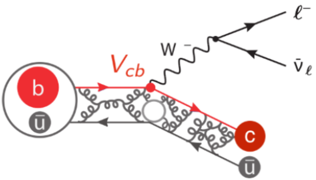
Tagging techniques

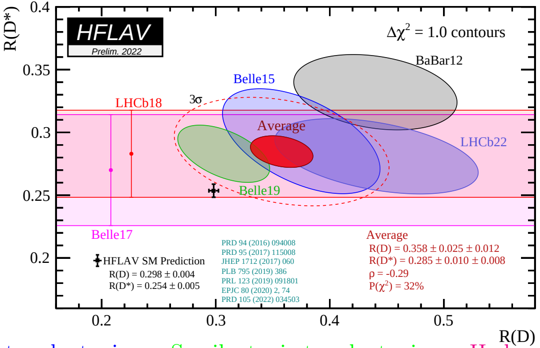
Purity →

← Efficiency

Inclusive	**Semileptonic**	**Hadronic**
$B \to$ anything	$B \to D^{(*)}\ell\nu_\ell$	$B \to$ hadrons
$\epsilon \approx \mathcal{O}(2\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$
Very large statistics; Also very large background	Mid-range reconstruction efficiency; Less information about B_{tag} due to neutrino	Cleaner sample Knowledge of $p(B_{\text{sig}})$; Lower tagging efficiency

- Very clean prediction from theory.
- New Physics could change the ratios $\boldsymbol{\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\overline{B}\to D^{(*)}\tau\nu)}{\mathcal{B}(\overline{B}\to D^{(*)}\ell\nu)}}$.
- Effect could be different for D and D^*.
- World average 3.1σ away from SM.





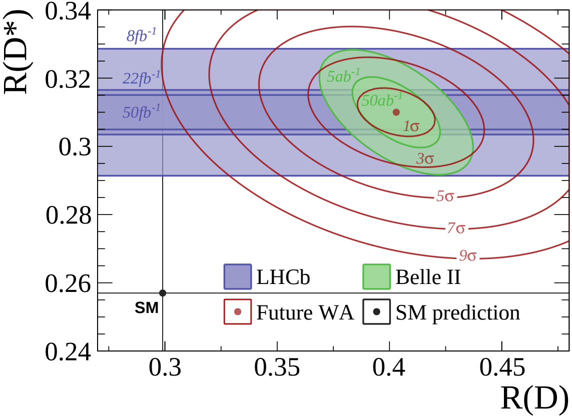
Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ

BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

$\overline{B} \to D^{(*)}\tau\overline{\nu}$ with Belle II & LHCb

arXiv:1709.10308: J. Albrecht, F. U. Bernlochner, M. Kenzie, S. Reichert, D. M. Straub, A. Tully

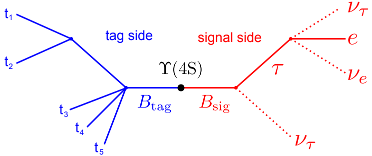
Measurement	SM prediction	Current World Average	Current Uncertainty	Projected Uncertainty[1] Belle II $5ab^{-1}$ 2020	Belle II $50ab^{-1}$ 2024	LHCb $8fb^{-1}$ 2019	LHCb $22fb^{-1}$ 2024	LHCb $50fb^{-1}$ 2030
$R(D)$	(0.299 ± 0.003)	$(0.403 \pm 0.040 \pm 0.024)$	11.6%	5.6%	3.2%	-	-	-
$R(D^*)$	(0.257 ± 0.003)	$(0.310 \pm 0.015 \pm 0.008)$	5.5%	3.2%	2.2%	3.6%	2.1%	1.6%

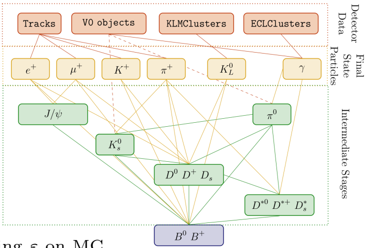


[1] *Projected uncertainties not including improvements in detectors and algorithms*

Improved algorithms @ Belle II

New Full Event Interpretation (FEI) algorithm for tag-side reconstruction



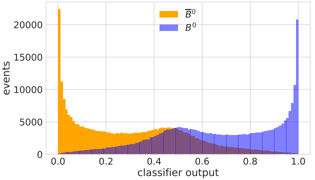


Tagging ε on MC

Tag	FR[1]	FEI Belle	FEI Belle II
Hadronic B^+	0.28%	0.76%	0.66%
SL B^+	0.67%	1.80%	1.45%
Hadronic B^0	0.18%	0.46%	0.38%
SL B^0	0.63%	2.04%	1.94%

[1] Belle Full Reconstruction algorithm.

Deep NN based flavor tagger

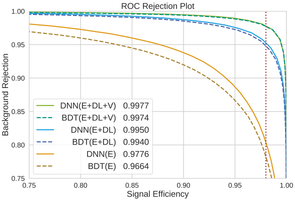


Tagging ε on MC

	Category-based	Deep NN
Belle II MC	$33.29 \pm 0.01\%$	$40.69 \pm 0.03\%$
Belle MC	$29.30 \pm 0.10\%$[2]	$34.42 \pm 0.09\%$

[2] Belle flavor tagger

Deep NN based $e^+e^- \to q\bar{q}$ background suppression



Electroweak penguin decays $b \to s\, l^+ l^-$

- Within the SM, decays proceed via one loop diagram:

  JHEP0712:040,2007

  $$\mathcal{R}_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 1.00030^{+0.00010}_{-0.00007}$$

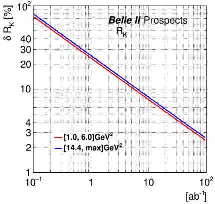
- In 2021, LHCb reported a 3.1σ deviation for the dilepton invariant mass squared region $1.1 < q^2 < 6\ \text{GeV}^4/c^2$:

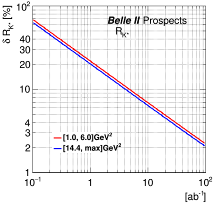
  $$\mathcal{R}_K = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

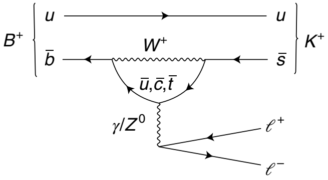
  Nature Physics 18, (2022) 277-282

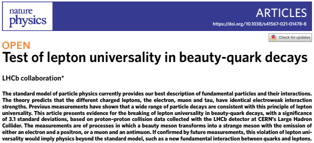
  (This supercedes a tension reported in 2019 w/5fb^{-1})

- Electrons and muons have the same ε at Belle II:
  $\Rightarrow$ *Both low and high* q^2 *regions possible.*









nature physics

ARTICLES

https://doi.org/10.1038/s41567-021-01478-8

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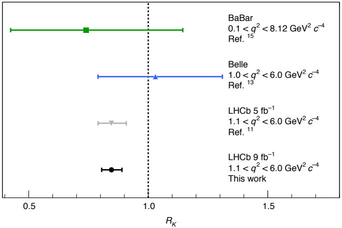
Test of lepton universality in beauty-quark decays

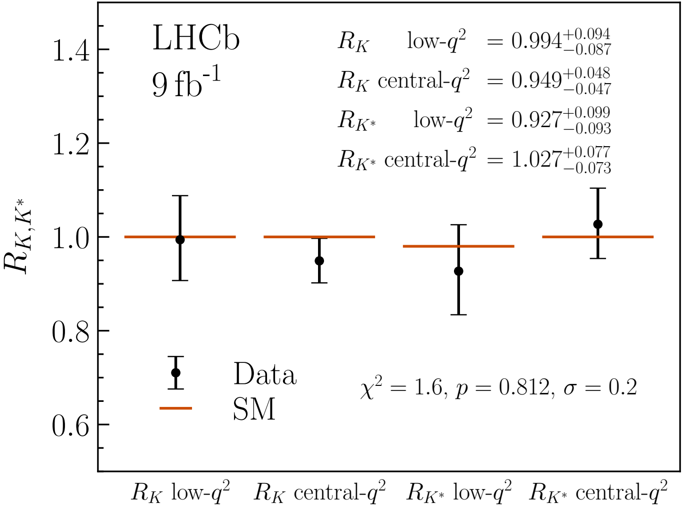
LHCb collaboration*

The standard model of particle physics currently provides our best description of fundamental particles and their interactions. The theory predicts that the different charged leptons, the electron, muon and tau, have identical electroweak interaction strengths. Previous measurements have shown that a wide range of particle decays are consistent with this principle of lepton universality. This article presents evidence for the breaking of lepton universality in beauty-quark decays, with a significance of 3.1 standard deviations, based on proton–proton collision data collected with the LHCb detector at CERN's Large Hadron Collider. The measurements are of processes in which a beauty meson transforms into a strange meson with the emission of either an electron and a positron, or a muon and an antimuon. If confirmed by future measurements, this violation of lepton universality would imply physics beyond the standard model, such as a new fundamental interaction between quarks and leptons.



$R(K^{(*)})$ anomaly vanishes in 12/2022

https://indico.cern.ch/event/1187945/



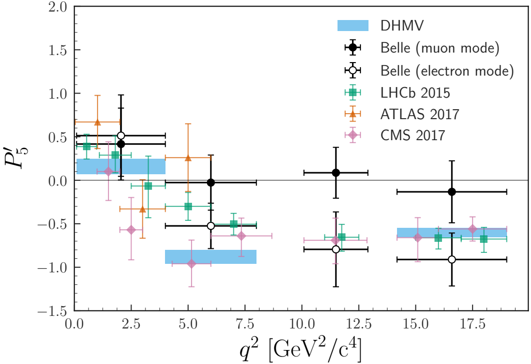
2017 ATLAS & CMS results, and lepton-flavor-dependent angular analysis by Belle

Plot: S. Wehle

Belle: PRL 118, 111801 (2017)

- Largest deviation of 2.6σ from the SM for the muon channel for $4 < q^2 < 8\ \text{GeV}^4/c^2$.
- Electron channel deviation of 1.1σ.

- Belle II and LHCb will be comparable for this process.
- Belle II will be able to perform an isospin comparison of K^{*+} and K^{*0}, or the ground states K.



Belle II sensitivity of P_5'

q^2 (GeV^2)	Belle	Belle II (50ab^{-1})
0.10 - 4.00	0.416	0.059
4.00 - 8.00	0.277	0.040
10.09 - 12.00	0.344	0.049
14.18 - 19.00	0.248	0.033

Neutrino electroweak penguin decays

⇒ The ultimate test of Belle II

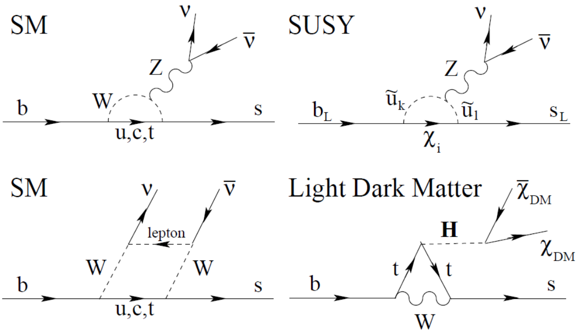
Neutrino EWP decays $b \to s\nu\bar{\nu}$: SM and NP

Electroweak-penguin (EWP) decays with 2 ν's in the final state.

Theoretically clean due to a maximum of one electromagnetically interacting charged particle in the final state, as opposed to $K^{(*)}l^+l^-$ decays.

Recall, FCNC are forbidden in the SM at tree level, but allowed at loop level.

⇒ *Very sensitive to NP entering the loops. Several new physics models (SUSY, non-standard Z coupling) could enhance these decays. Can probe higher mass scales than direct searches.*

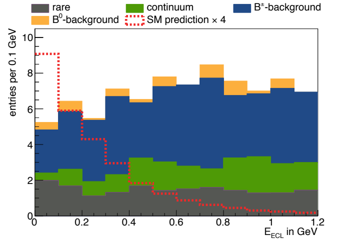


Signal extraction

Extract the signal yield by fitting the Extra Energy in the Calorimeter:

Sum of energies of neutral clusters not associated with reconstructed particles

$$E_{ECL} = \sum E_{\text{Calor.}} - \left(\sum E_{\text{tag}} + \sum E_{\text{sig}}\right)$$



Extensive Toy MC studies performed to estimate sensitivity: 1K bkgd.-only samples generated and fit for yield estimate. Fit bias estimated from ensemble tests and corrected for in fit to data. (plot for $K^+\nu\bar{\nu}$)

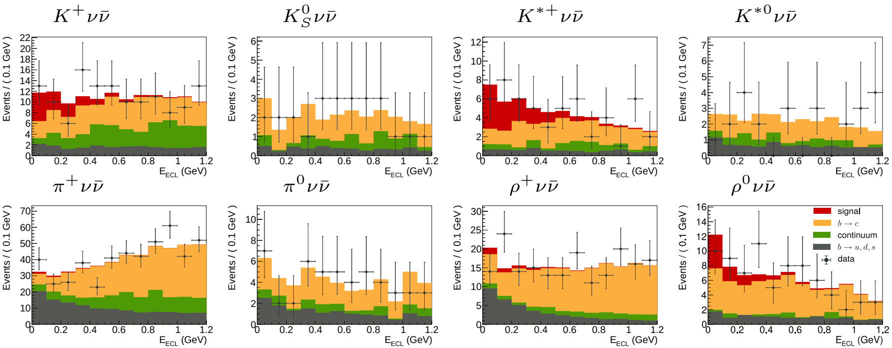
Charm B decay & $q\bar{q}$ background for $K^+\nu\bar{\nu}$ in $E_{ECL} \in (0, 1.2)$ GeV.

Dominant $b \to c$ contribution from semileptonic B decays.

	contribution in %
continuum	22.6
2 leptons missing	15.3
K_Ls and lepton missing	6.5
lepton and hadrons missing	24.1
2 charged hadrons missing	1.7
wrong B type	3.8
hadronic, K_L missing	24.1
hadronic π^0 missing	1.0
no match	0.0
other	1.0

Fit to data

Extended binned ML fit to E_{ECL}:



- Histogram templates to model signal and bkgds from charm B decay, charmless B decay, and continuum.
- Relative fractions of the background components fixed to MC expectations.
- Signal and overall background yield allowed to vary.

Channel	Observed N_{sig}	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K_S^0\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	$0.0\,\sigma$
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	$0.0\,\sigma$
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	$0.3\,\sigma$
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	$1.2\,\sigma$

Upper limits

- **Expected (exp.) and observed upper limits at the 90% confidence level** (including systematic uncertainties)

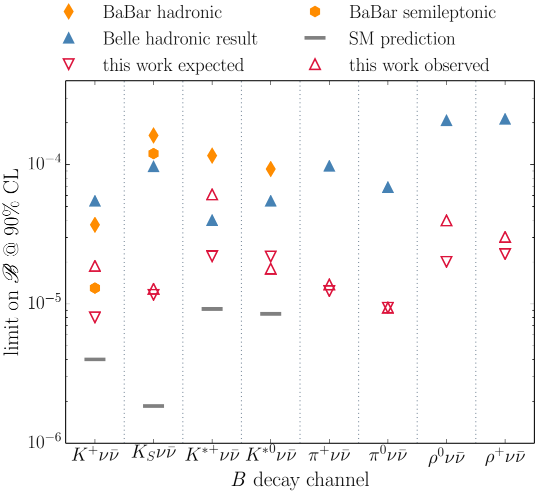
Channel	Efficiency	Expected Limit	Measured Limit
$K^+\nu\bar{\nu}$	2.16×10^{-3}	0.8×10^{-5}	1.9×10^{-5}
$K^0_S\,\nu\bar{\nu}$	0.91×10^{-3}	1.2×10^{-5}	1.3×10^{-5}
$K^{*+}\nu\bar{\nu}$	0.57×10^{-3}	2.4×10^{-5}	6.1×10^{-5}
$K^{*0}\nu\bar{\nu}$	0.51×10^{-3}	2.4×10^{-5}	1.8×10^{-5}
$\pi^+\nu\bar{\nu}$	2.92×10^{-3}	1.3×10^{-5}	1.4×10^{-5}
$\pi^0\nu\bar{\nu}$	1.42×10^{-3}	1.0×10^{-5}	0.9×10^{-5}
$\rho^+\nu\bar{\nu}$	1.11×10^{-3}	2.5×10^{-5}	3.0×10^{-5}
$\rho^0\nu\bar{\nu}$	0.82×10^{-3}	2.2×10^{-5}	4.0×10^{-5}

Combine charged and neutral modes:

- The systematic uncertainties are evaluated on independent MC and data control samples for charged and neutral modes.
  $\Rightarrow$ *Can be considered uncorrelated.*
- Add the -$\mathcal{L}$ and scale the $\mathcal{B}$ of the neutral modes by τ_B^+/τ_B^0 and repeat the calculation of the limit:

$$\mathcal{B}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$
$$\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$$
$$\mathcal{B}(B \to \pi\nu\bar{\nu}) < 0.8 \times 10^{-5}$$
$$\mathcal{B}(B \to \rho\nu\bar{\nu}) < 2.8 \times 10^{-5}$$

Comparison with other measurements

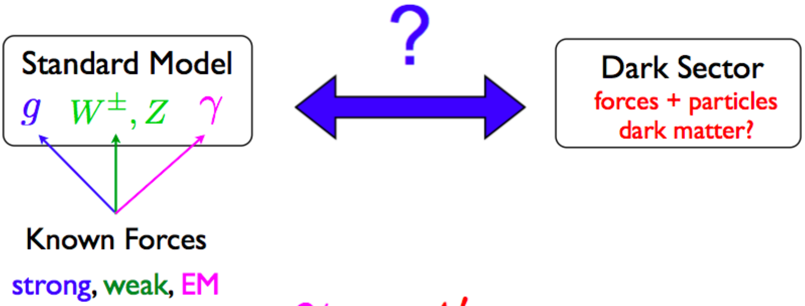


Worlds most stringent limits obtained for:

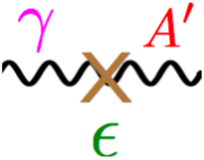
$$B^0 \to K_S^0\nu\bar{\nu},\ \ B^0 \to K^{*0}\nu\bar{\nu},\ \ B^{+/0} \to \pi^{+/0}\nu\bar{\nu},\ \ B^{+/0} \to \rho^{+/0}\nu\bar{\nu}$$

Dark sector

- Dark matter suggests the presence of a dark sector, neutral under all Standard Model forces (i.e. non-WIMP)



One way: Dark Photons.



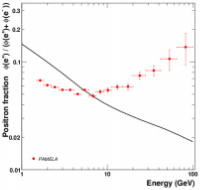
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

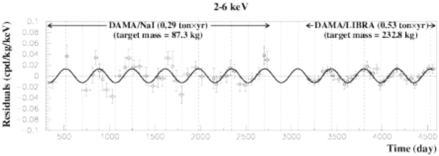
"Kinetic Mixing" Holdom

Galison, Manohar

Dark sector

- recently strong interest in dark sector models
- introduce a vector boson A, and often a dark Higgs h' by a Higgs mechanism
- can explain the inconsistencies observed in astrophysical data and dark matter experiments
  - positron excess but no $\bar{p}$ excess (PAMELA - figure left)
  - direct detection of dark matter (DAMA/LIBRA - figure right)

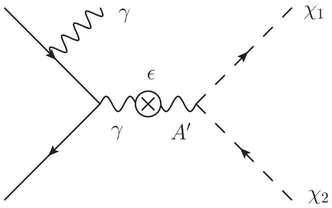




PAMELA, Nature 458, 607-609 (2009)
DAMA/LIBRA, Eur. Phys. J. C (2008) 56: 333-355

M. Pospelov et al., arXiv:0711.4866
N. Arkami-Hamed et al., arXiv:0810.0713
E.J. Chun et al., arXiv:0812.0308
C. Cheung et al., arXiv:0902.3246
A. Katz et al, arXiv:0902.3271
D. Morrissey et al., arXiv:0904.2567

Dark Photon

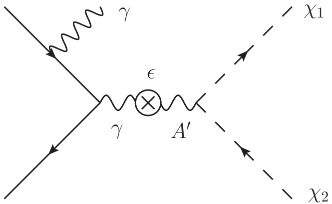


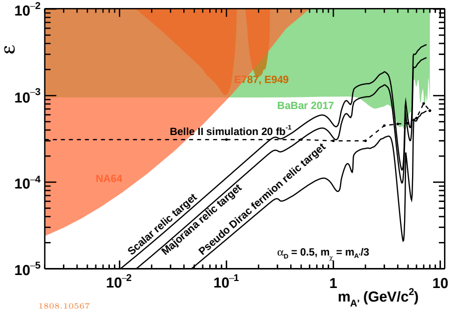
- Massive vector particle A' mixes with the SM γ.
- Can decay to experimentally invisible $A' \rightarrow \chi_1\chi_2$ final state.

⇒ Require ISR γ:

$$E_{\gamma ISR} = \frac{s - m_{A'}^2}{2\sqrt{s}}$$

Dark Photon

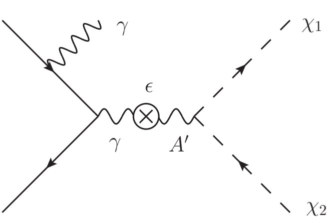


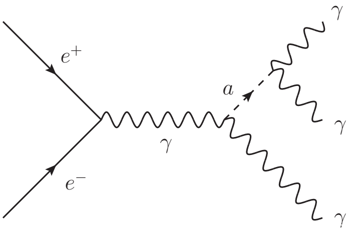


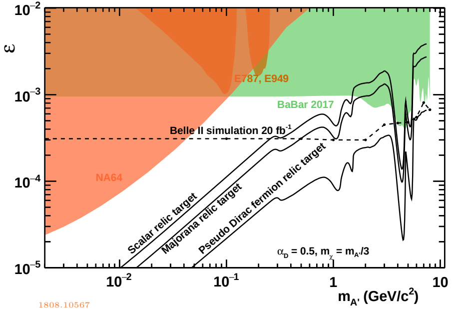
1808.10567

Dark Photon

ALPs







1808.10567

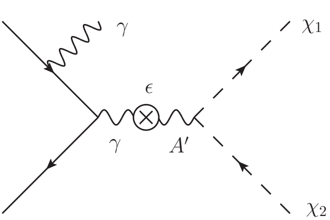
- ALP-strahlung experimentally easier than γ-fusion.
- Three photons within tracking acceptance:

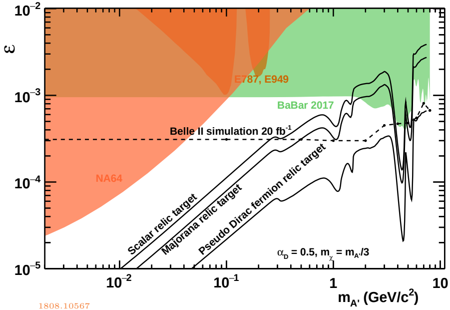
  $\Rightarrow$ Add up to beam energy.

  – Zero tracks.

  – Bump in di-γ mass.

Dark Photon





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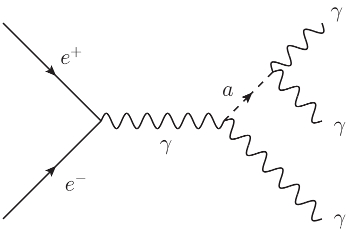
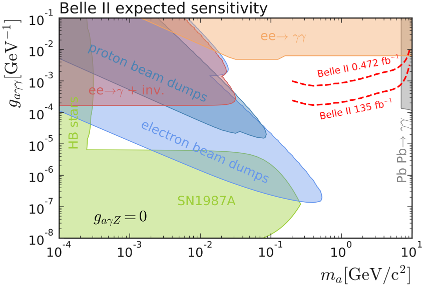
ALPs





No systematics. 1709.00009

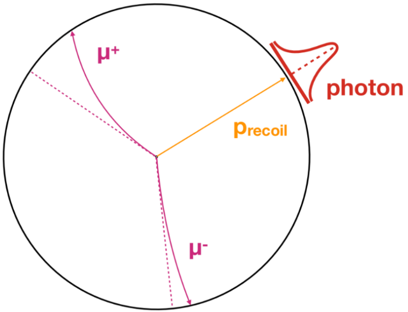
Only dominant $e^+e^- \to \gamma\gamma\gamma$ background included.

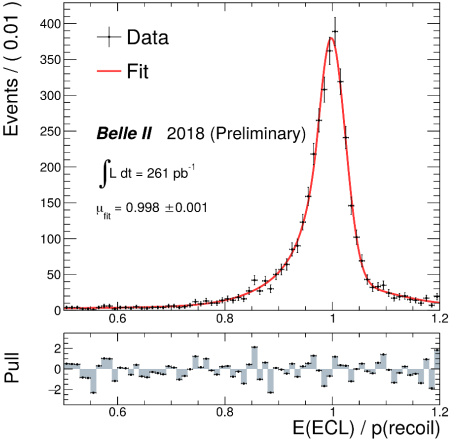
135fb^{-1} assumes no $\gamma\gamma$ trigger veto in the barrel.

Neutral Reconstruction: *Key Belle II Strength*

Radiative dimuon events in first data

$$e^+e^- \to \mu^+\mu^-\gamma$$





Neutral Reconstruction: *Key Belle II Strength*

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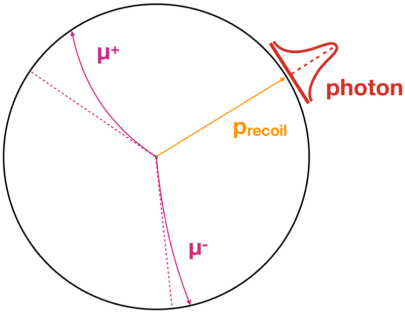
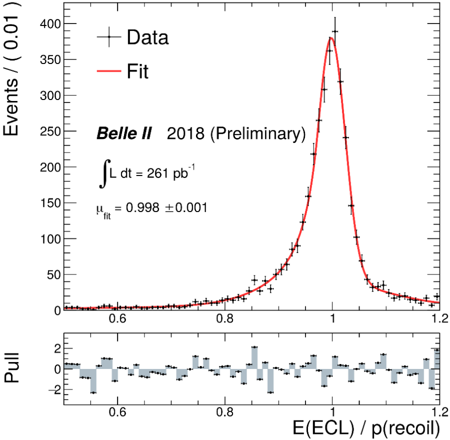




⇒ ***Ready for dark matter searches with NEW single & triple photon triggers***

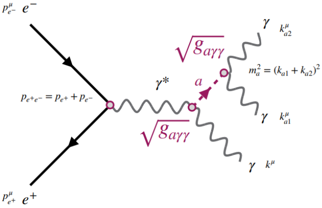
First Belle II publication

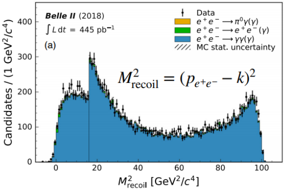
Axionartige Teilchen

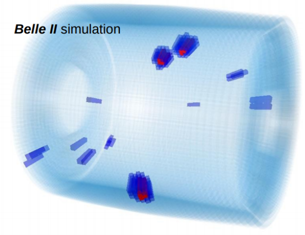
PHYSICAL REVIEW LETTERS **125**, 161806 (2020)

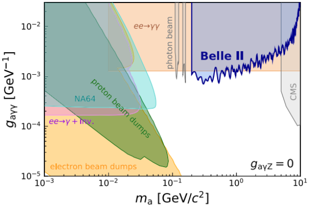
Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II

F. Abudinén,[42] I. Adachi,[21,18] H. Aihara,[115] N. Akopov,[121] A. Aloisio,[87,35] F. Ameli,[39] N. Anh Ky,[32,11] D. M. Asner,[2] T. Aushev,[23] V. Aushev,[77] V. Babu,[9] S. Baehr,[46] S. Bahinipati,[25] P. Bambade,[96] Sw. Banerjee,[105] S. Bansal,[68] J. Baudot,[97] J. Becker,[46] P. K. Behera,[27] J. V. Bennett,[109] E. Bernieri,[40] F. U. Bernlochner,[99] M. Bertemes,[29] M. Bessner,[102]

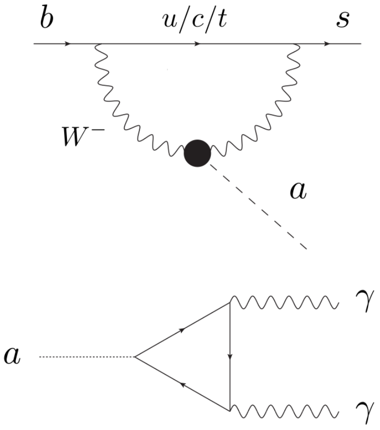




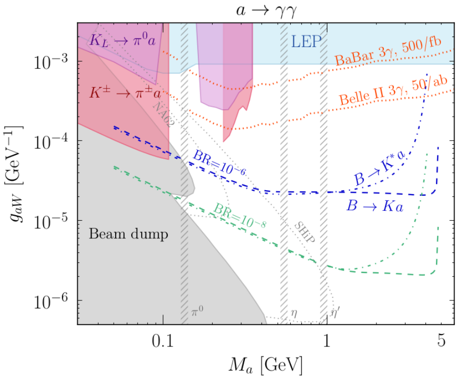




- When axion-like particles couple to SU(2) gauge bosons, they can be produced in rare B decays

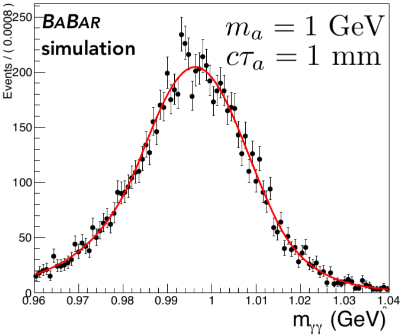


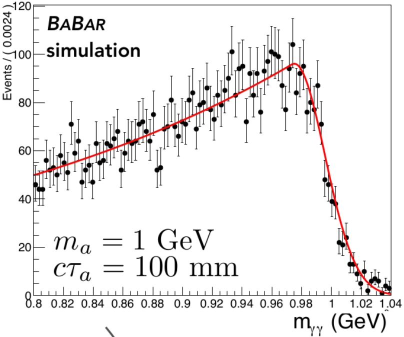
[2]

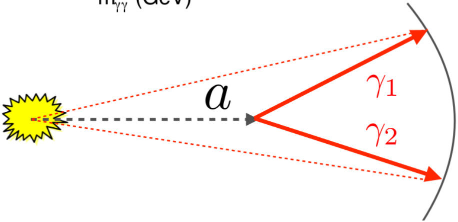


Slides 30-33 from Brian Shuve's talk at the Long-lived particles at Belle II workshop.

LLP signal shape

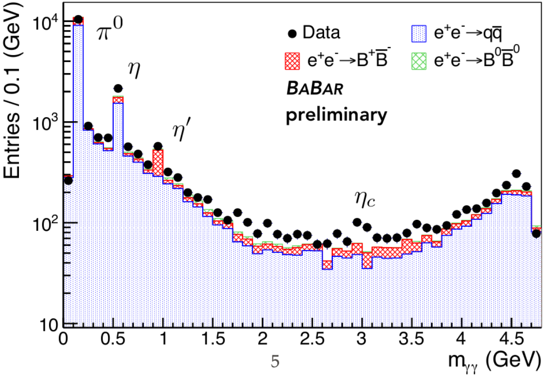






Analysis strategy

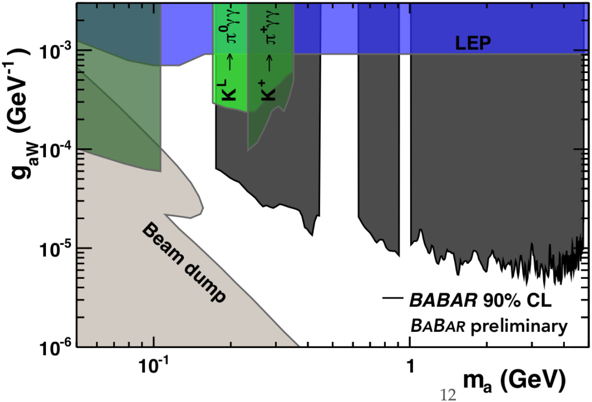
- Reconstruct $B^{\pm} \to K^{\pm} a,\ a \to \gamma\gamma$ candidates, look for narrow peak in diphoton invariant mass spectrum
- Train a BDT using signal & background MC events, include shape variables, kinematic information, track/cluster multiplicities, PID,…



5

Limits on ALP coupling

- The coupling g_{aW} predicts both ALP BF and lifetime
- Use limit on BF as function of lifetime to set limit on g_{aW}



12

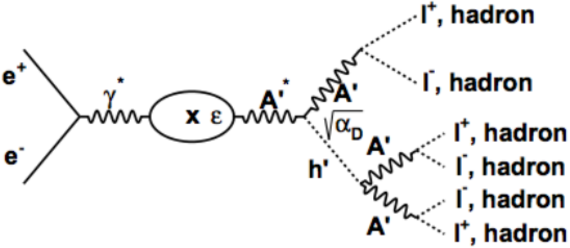
- Improve limit on coupling by over 2 orders of magnitude for many masses!

Belle II analysis starting at KIT now (WS19/20 TP2 student)

Additional channels: challenging combinatorics

Search for the dark Photon and dark Higgs boson in 6-body FS at Belle.

$$e^+e^- \to Ah' \to AAA \text{ with } A \to l^+l^-(l = e, \mu) \text{ or hadrons}$$



Phys. Rev. Lett. **114**, 211801 (2015)

New physics in right handed currents

Right-handed currents

Despite the tremendous success of the SM, there are still open questions that are unanswered and motivate further model-building. E.g.,

1) Quark and Lepton flavour & mass hierarchy,
2) Matter dominance.

A common model-building steps towards solving such grand questions is to extend the gauge structure of the SM.

One of the simplest extensions involves an additional **right handed SU(2)**.

$\Rightarrow$ *New heavy gauge bosons W, Z and new heavy charged and neutral Higgs particles.*

$\Rightarrow$ *Quark flavour mixing matrices $V_L = V_{CKM}$ and V_R describing left- and right-handed charged current interactions; introduces 5 additional CP phases.*

Recall the mass hierarchy of the elementary particles

$\begin{pmatrix} m_\nu, \\ m_u, \\ \vdots \end{pmatrix}$

in units of **GeV = 10^9eV**

Families ↓

Families				
1	ν_e (≈0)	ν_μ (≈0)	ν_τ (≈0)	$< 10^{-9}$
2	e^- ($5\cdot10^{-4}$)	μ^- (0.105)	τ^- (1.78)	
3	u ($3\cdot10^{-3}$)	c (1.3)	t (170)	
4	d ($6\cdot10^{-3}$)	s (0.100)	b (4.5)	

Very hierarchical structure

Particles in a given family distinguished only by the mass!

Quarks

$\begin{pmatrix} u \\ d' \end{pmatrix}_L \begin{pmatrix} c \\ s' \end{pmatrix}_L \begin{pmatrix} t \\ b' \end{pmatrix}_L$ $\quad u_R \; c_R \; t_R \quad + 2/3$

$\qquad\qquad\qquad\qquad\quad d_R \; s_R \; b_R \quad - 1/3$

+ Leptons

Fundamental Forces

Gauge Theory : $\underbrace{SU(3)}_{QCD} \otimes SU(2)_L \otimes U(1)_Y$ → $U(1)_{QED}$

Strong Interactions **(Gluons)**

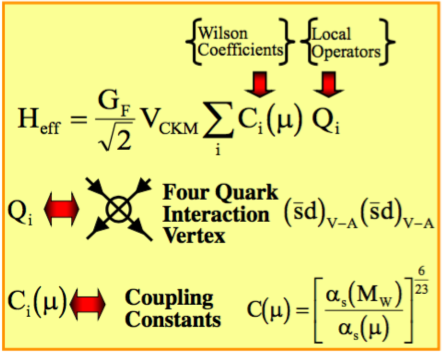
Electroweak Interactions **($W^{\pm}$, Z^0, γ)**

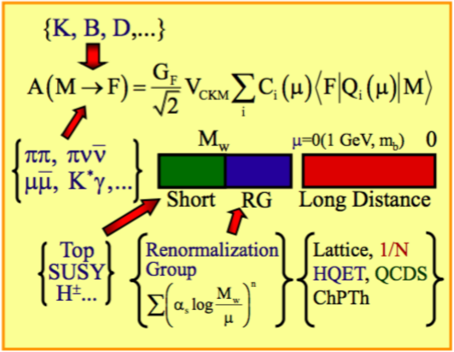
Neutral Higgs

→ Charged Current Interactions only between left-handed Quarks

$$\frac{g_2}{2\sqrt{2}} \gamma_\mu (1 - \gamma_5) \cdot V_{td}$$

Operator product expansion in the SM





Operators: SM and NP

$b \to s_L$ (SM) $\qquad$ $b \to s_L$ (NP)

- QCD Penguin operators

$$Q_{3,5} = (\bar{s}b)_{V-A}\,(\bar{q}q)_{V\mp A} \quad \to \tilde{Q}_{3,5} = (\bar{s}b)_{V+A}\,(\bar{q}q)_{V\pm A}$$
$$Q_{4,6} = (\bar{s}_i b_j)_{V-A}\,(\bar{q}_j q_i)_{V\mp A} \to \tilde{Q}_{4,6} = (\bar{s}_i b_j)_{V+A}\,(\bar{q}_j q_i)_{V\pm A}$$

- Chromo/Electromagnetic Dipole Operators

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu} \to \tilde{Q}_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1-\gamma_5) b_i F_{\mu\nu}$$
$$Q_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu}(1+\gamma_5) t^a b G^a_{\mu\nu} \to \tilde{Q}_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu}(1-\gamma_5) t^a b G^a_{\mu\nu}$$

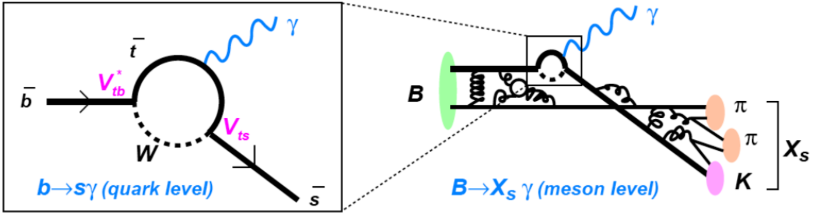
- Electroweak Penguin Operators

$$Q_{7,9} = \frac{3}{2}(\bar{s}b)_{\mathrm{V-A}}\, e_q\, (\bar{q}q)_{\mathrm{V\pm A}} \quad \to \tilde{Q}_{7,9} = \frac{3}{2}(\bar{s}b)_{\mathrm{V+A}}\, e_q\, (\bar{q}q)_{\mathrm{V\mp A}}$$
$$Q_{8,10} = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V-A}}\, e_q\, (\bar{q}_j q_i)_{\mathrm{V\pm A}} \to \tilde{Q}_{8,10} = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V+A}}\, e_q\, (\bar{q}_j q_i)_{\mathrm{V\mp A}}$$

Right-handed current is a signature of new physics

Where can we search for RH currents?

Flavor changing neutral current transitions (FCNC): *change the flavor of a fermion current without altering it's electric charge*



FCNC in SM only possible via loops.

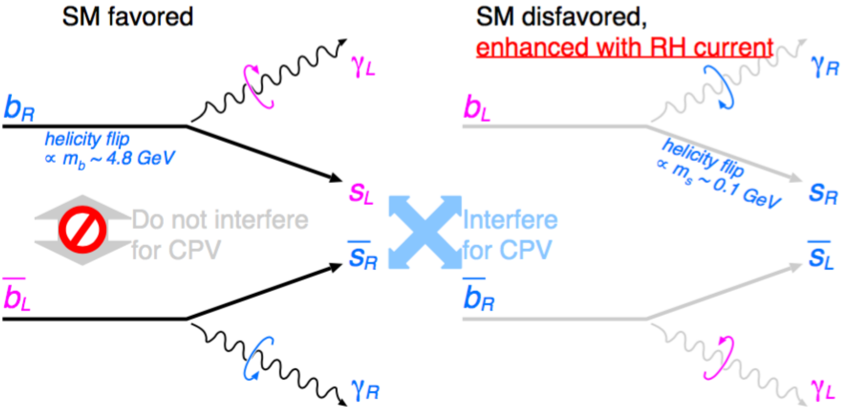
New physics contribution can be comparable and even dominating to (small) SM amplitudes.

New physics appears not only in modifications of branching fractions, but also in asymmetries (e.g., CP) and in angular effects.

⇒ *Sensitive also to spin structure of new physics*

How do you measure RH currents?

The most powerful method is with time-dependent CP violation measurements in $B \to K^*(K_S^0\pi^0)\gamma$ decays.



Time-dependent CP asymmetry in $B \to K^*(K_S^0\pi^0)\gamma$

$$\mathcal{A}(\Delta t) = S\sin(\Delta m \Delta t) + A\cos(\Delta m \Delta t)$$

Possible due to interference with mixing between dominant decay helicities

$$b \to s\gamma_L \qquad \text{or} \qquad \bar{b} \to \bar{s}\gamma_R$$

and suppressed decay helicities:

$$b \to s\gamma_R \qquad \text{or} \qquad \bar{b} \to \bar{s}\gamma_L$$

In SM one naively expects:

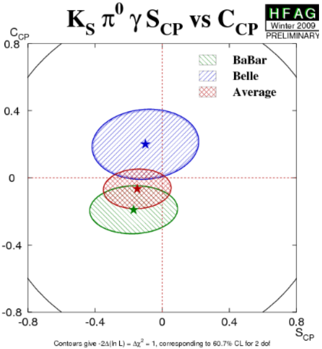
$$S_{K_S^0\pi^0\gamma} = -2\frac{m_s}{m_b}\sin 2\phi_1 \sim -0.03$$

Sensitive to helicity-changing NP contributions.

Example: Left-Right symmetric model

$$\to S_{K_S^0\pi^0\gamma} \sim 0.67\cos 2\phi_1 \sim 0.5$$

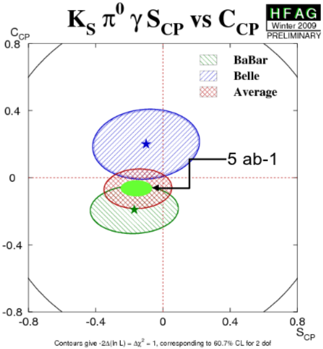
$B \to K^*\gamma$ at B-factories



$$S = -0.16 \pm 0.22 \qquad C = -0.04 \pm 0.14$$

Measurements statistically limited

$B \to K^*\gamma$ at B-factories



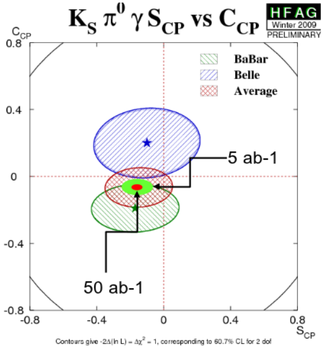
$$S = -0.16 \pm 0.22 \qquad C = -0.04 \pm 0.14$$

Measurements statistically limited

$$\Downarrow$$

$$\sigma(S_{K^*\gamma}) \approx 0.09 \;\; @ \;\; 5\ \text{ab}^{-1}$$

$B \to K^*\gamma$ at B-factories

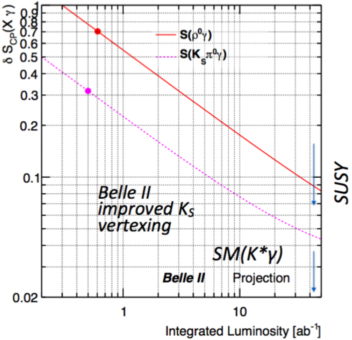


$$S = -0.16 \pm 0.22 \qquad C = -0.04 \pm 0.14$$

Measurements statistically limited

$$\Downarrow$$

$$\sigma(S_{K^*\gamma}) \approx 0.09 \quad @ \quad 5\ \text{ab}^{-1}$$
$$\approx 0.03 \quad @ \quad 50\ \text{ab}^{-1}$$



$$S = -0.16 \pm 0.22 \qquad C = -0.04 \pm 0.14$$

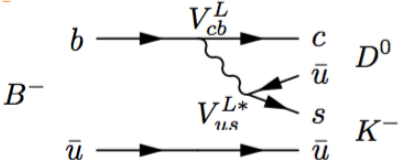
Measurements statistically limited

$$\Downarrow$$

$$\sigma(S_{K^*\gamma}) \approx 0.09 \quad @ \quad 5 \text{ ab}^{-1}$$
$$\approx 0.03 \quad @ \quad 50 \text{ ab}^{-1}$$

RH currents also modify CKM angle $\phi_3(\gamma)$

Additional CP phases from right-handed charged current interactions



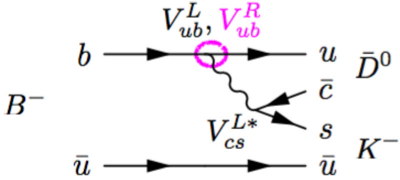
$$A(B^+ \to \bar{D}^0 K^+) = A_B\,,$$

$$A(B^+ \to D^0 K^+) = A_B r_+ e^{i(\phi_{DK}+\delta_{DK})}$$

$$A(B^- \to D^0 K^-) = A_B\,,$$

$$A(B^- \to \bar{D}^0 K^-) = A_B r_- e^{i(-\phi_{DK}+\delta_{DK})}$$

SM null test: $r_+ = r_-$ in SM



$$A_{CP}(B^+ \to D^0 K^+) = \frac{\Gamma(B^+ \to D^0 K^+) - \Gamma(B^- \to \bar{D}^0 K^-)}{\Gamma(B^+ \to D^0 K^+) + \Gamma(B^- \to \bar{D}^0 K^-)} = \frac{r_+^2 - r_-^2}{r_+^2 + r_-^2}\,,$$

RH currents also modify CKM angle $\phi_3(\gamma)$

$$A(B^+ \to D^0 K^+) = |A_L| e^{i(\phi_3^L + \delta_L)} + |A_R| e^{i(\phi_3^R + \delta_R)}$$

$$A(B^- \to \bar{D}^0 K^-) = |A_L| e^{i(-\phi_3^L + \delta_L)} + |A_R| e^{i(-\phi_3^R + \delta_R)}$$

$$\phi_3^{L(R)} \;=\; \arg(V_{ub}^{L(R)*})$$

$$R_{DK} = e^{2i\phi_3^L} \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^+ \to D^0 K^+)} = \frac{1 + |A_R/A_L| e^{i(-\phi_3^R + \phi_3^L + \delta)}}{1 + |A_R/A_L| e^{i(\phi_3^R - \phi_3^L + \delta)}}$$

$$A_{CP}(B^+ \to D^0 K^+) = \frac{1 - |R_{DK}|^2}{1 + |R_{DK}|^2}$$

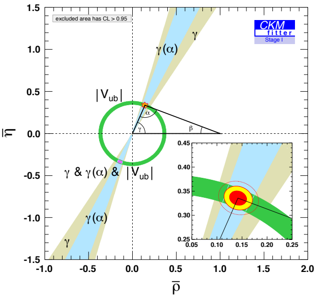
$$\phi_{DK} = \phi_3^L - \arg(R_{DK})/2 \,.$$

Summary

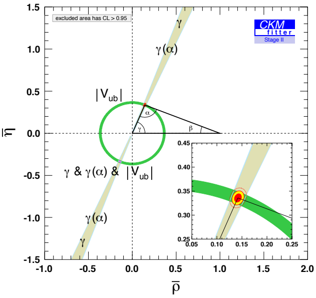
- Belle II expects to improve precision to $\alpha \approx 0.3^\circ$, $\beta \approx 1.0^\circ$, $\gamma \approx 1.5^\circ$.
- Improvement in precision should help to resolve the tension in $\mathcal{R}(D^{(*)})$, $\mathcal{R}(K)$, inclusive and exclusive measurements of $|V_{ub}|$ and $|V_{cb}|$, and more.

Future sensitivities *assuming data consistent with the SM* (arXiv:1309.2293)

Belle 5ab^{-1}, LHCb 7fb^{-1} (2020)



Belle 50ab^{-1}, LHCb 50fb^{-1} (2030)



New physics is out there. Let's hope this isn't future of the UT!

Extra reading

F. Bernlochner *et al.*, *Semitauonic b-hadron decays: A lepton flavor universality laboratory.*

https://arxiv.org/pdf/2101.08326.pdf

G. Ciezarek1 *et al.*, *A Challenge to Lepton Universality in B Meson Decays.*

https://arxiv.org/pdf/1703.01766.pdf